

Title: Sea Spray and Icing in the Emerging Open Water of the Arctic Ocean

POP: 6/15/2014–6/14/2015

CDRL A002: Progress Report Technical

Award Number: N00014-12-C-0290

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Total contract amount: \$286,205

Costs incurred through April 30, 2015: \$214,960

Estimate to complete: \$71,245

ABSTRACT

With the sea ice cover in the Arctic Ocean declining, the more extensive areas of open water will foster more frequent storms, higher winds, and bigger waves. These conditions can create copious amounts of sea spray. We anticipate that structures placed in shallow water—wind turbines, drilling rigs, or man-made production islands, for instance—will, therefore, experience more episodes of freezing spray that will create hazards for both personnel on these structures and for the structures themselves. The extra salt carried by the spray will also accelerate corrosion. Few observations, however, have been made of sea spray generation in high winds, above, say, 15–20 m/s; and no spray observations have been made in freezing temperatures. Our objective is, thus, to observe the size distribution and rate of creation of spray droplets at air temperatures below freezing and in winds above 15 m/s—and, preferably, above 20 m/s.

Climatologically, Mt. Desert Rock, a small, well exposed island 24 miles into the Atlantic Ocean from Bar Harbor, Maine, provided just such conditions in January. Andreas and collaborator Kathy Jones thus spent most of January 2013 observing sea spray and measuring relevant meteorological and ocean conditions on Mt. Desert Rock. We are continuing our data analysis but did encounter frequent winds near 20 m/s and temperatures below freezing during our deployment.

LONG-TERM GOALS

The goal of this project is to develop the capability to quantify both the concentration of sea spray over the open ocean and the severity of sea spray icing on fixed offshore structures. We will use existing information on the relationship of the spray concentration distribution to wind speed (Lewis and Schwarz 2004; Andreas et al. 2010; Jones and Andreas 2012) and our own analysis of data from Mt. Desert Rock to estimate the sea spray climatology in ice-free northern oceans from reanalysis data and the time-varying extent of the sea ice cover. Our field campaign focused on measuring sea spray parameters and relevant meteorological conditions to characterize spray droplet distributions at high wind speeds and low temperatures. Sea spray data at high wind speeds are sparse, and there are no

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 12 JUN 2015		2. REPORT TYPE		3. DATES COVERED 15-06-2014 to 14-06-2015	
4. TITLE AND SUBTITLE Sea Spray and Icing in the Emerging Open Water of the Arctic Ocean			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NorthWest Research Associates, Inc., 4118 148th Avenue NE, Redmond, WA, 98052			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 11	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

measurements of the spray droplet concentration at air temperatures below freezing. This effort directly addresses two of the focus areas in the core ONR Arctic program:

- Improving understanding of the physical environment and processes in the Arctic Ocean.
- Developing integrated ocean-ice-wave-atmosphere Earth system models for improved predictions on time scales of days to months.

OBJECTIVES

Our objectives are as follows:

- Use reanalysis data to estimate spatially and temporally distributed sea spray concentrations over the northern oceans. Such estimates are currently limited by the sparse information on sea spray at high wind speeds. Adapt the Andreas et al. (2008, 2010, 2015) spray algorithms for high wind speeds and subfreezing temperatures.
- Use these estimates of sea spray concentrations to characterize the icing risk for offshore structures in northern regions by adapting the heat balance calculation for freezing rain in Jones (1996) to saline droplets and by modifying the Finstad et al. (1988) collision efficiency algorithm to take into account the larger mass of saline droplets compared to freshwater droplets.
- Determine the properties of sea spray in high wind speeds by making droplet concentration measurements on fixed offshore structures or at well exposed coastal sites at air temperatures below freezing.
- Measure the density of ice accreted from sea spray on fixed structures and develop a relationship between spray ice density and weather parameters.
- Use our sea spray measurements to revise the Jones and Andreas (2012) spray concentration distribution for high wind speeds; update our initial icing risk analysis.
- Rapidly disseminate results.

APPROACH

This project is a collaboration between Andreas and Kathy Jones of the U.S. Army's Cold Regions Research and Engineering Laboratory, who is funded under a separate ONR award (N00014-12-MP-20085).

Our goal is to quantify the concentrations of wind-generated sea spray and the resulting spray icing on offshore structures, such as wind turbines and exploration, drilling, and production platforms. Our approach combines 1) simulating sea spray and icing from reanalysis data and data from moored buoys and coastal stations, 2) a field campaign to measure the quantity and size distribution of sea spray in high winds and low temperatures, 3) developing a function to predict spray concentration at high wind speeds, 4) estimating the spatial distribution of sea spray in all seasons, and 5) determining icing risk in the northern oceans when the air temperature is below freezing.

I will focus this report on the field campaign. Mt. Desert Rock is a small, low, unvegetated island 24 miles into the Atlantic from Bar Harbor, Maine. The island has hosted a lighthouse for 160 years. From NOAA instruments placed high on this lighthouse, we saw that, in January, Mt. Desert Rock experiences frequent episodes of winds of 20 m/s and air temperatures below freezing. We therefore carried out spray and meteorological measurements on the "Rock" in January 2013.

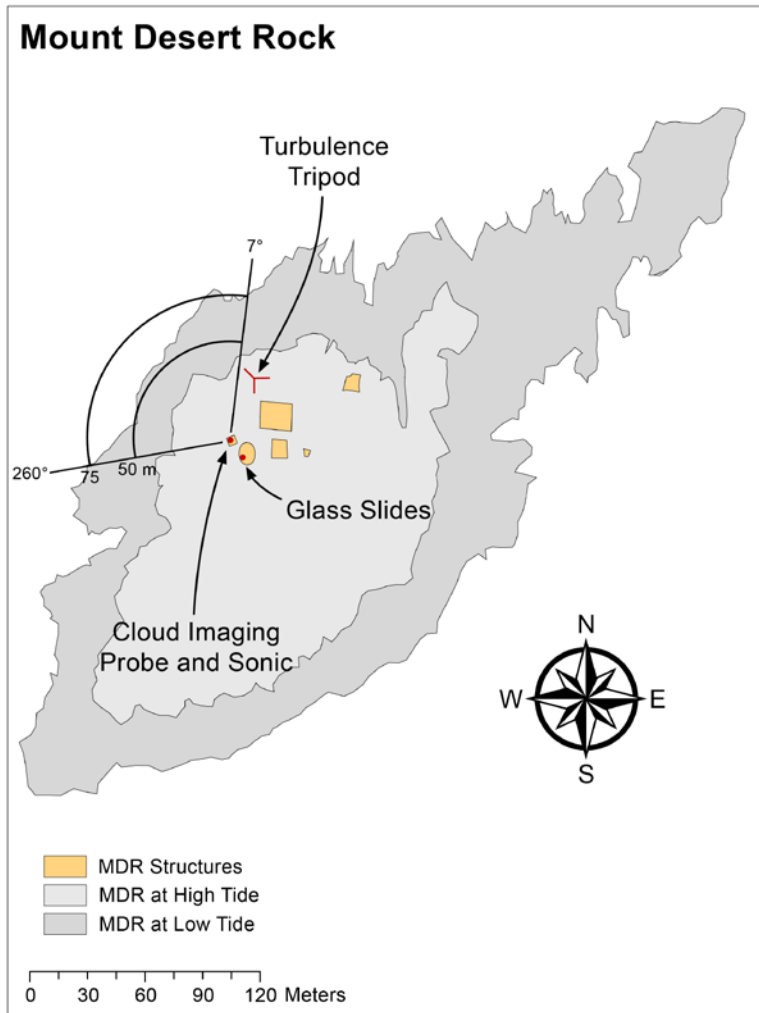


Figure 1. Map of Mt. Desert Rock showing its shoreline at low and high tide, the structures on the island, and locations of our instruments during our January 2013 experiment. The yellow oval is the lighthouse. The sector from 260° to 7° denotes the only wind directions we used in our analysis.

On Mt. Desert Rock, our primary instrument for observing sea spray was a cloud imaging probe, which we are borrowed from Chris Fairall of NOAA’s Earth System Research Laboratory. This device consists of an optical array; it images and then automatically sizes droplets moving through the array. It can size droplets with radii from $6.25\ \mu\text{m}$ up to $775\ \mu\text{m}$ in 62 bins that are each $12.5\ \mu\text{m}$ wide. We supplemented these data with more labor-intensive sampling—namely, counting and sizing droplets collected on Vaseline-coated glass slides.

To characterize the meteorological conditions in which we observed the spray and, thereby, to develop parameterizations for spray concentration and spray production rate, we also deployed a full suite of turbulence instruments. These instruments provided mean wind speed and direction, temperature, humidity, and pressure and the turbulent air-sea surface fluxes of momentum and sensible heat. Figure 1 shows the locations of the cloud imaging probe and its associated sonic anemometer, the turbulence instruments, and where we collected spray on glass slides on Mt. Desert Rock.

Figure 2 shows time series of wind speed, air temperature, and relative humidity during our stay on Mt. Desert Rock. Some of these data are our own measurements (“Ours,” from the turbulence tripod; and “Gill Sonic,” from the sonic anemometer attached to the cloud imaging probe); and some

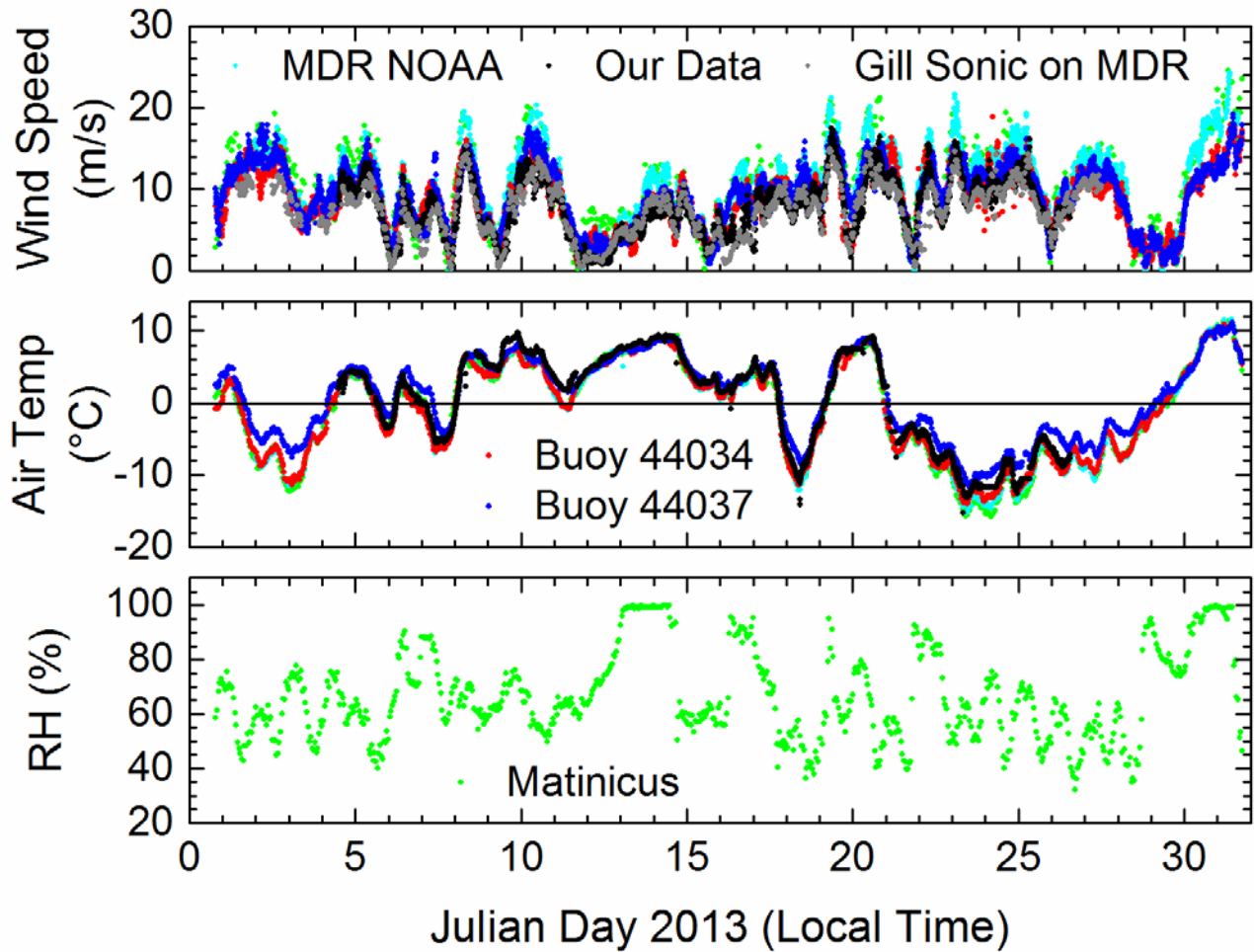


Figure 2. Wind speed, air temperature, and relative humidity during our deployment on Mt. Desert Rock (MDR). All legends refer to all panels. “MDR NOAA” refers to the NOAA instruments on the lighthouse; likewise, “Matinicus” denotes the NOAA instruments on Matinicus Rock. “Gill Sonic on MDR” is the wind speed from the Gill sonic anemometer associated with the cloud imaging probe (Figure 3). “Our Data” identifies the wind speed and temperature data from the turbulence tripod (Figure 1).

come from nearby buoys (44034 and 44037) and lighthouses (i.e., instruments on the Mt. Desert Rock lighthouse and on the Matinicus Rock lighthouse), both sets collected by NOAA’s National Data Buoy Center. Clearly, we encountered winds verging on 20 m/s and air temperatures frequently below freezing.

WORK COMPLETED

Most of this year’s work was analyzing and interpreting the data collected by the cloud imaging probe that we deployed on Mt. Desert Rock in January 2013. Figure 3 shows a picture of the cloud imaging probe (CIP) on Mt. Desert Rock and its associated Gill sonic anemometer/thermometer. This sonic measured wind speed and the wind direction at the CIP; both pieces of information are crucial for interpreting the raw CIP data.



Figure 3. The cloud imaging probe from Droplet Measurement Technologies and the Gill sonic anemometer/thermometer mounted on the foghorn platform on Mt. Desert Rock in January 2013.

Figure 4 shows sea spray concentration spectra that we measured in four wind speed ranges with the cloud imaging probe. All the data that we retained for analysis were collected when the average wind direction at the CIP was in the sector between 260° and 7° denoted in Figure 1. This is the sector for which the cloud imaging probe had the best exposure to the ocean.

Still, to assess whether the distance to the ocean influenced our observations, in Figure 4, we distinguish data collected when the tide was high and when the tide was low. That is, in Figure 4, the “High Water” data were collected when the tide was between its highest monthly level and its monthly mid-point. The “Low Water” data denote spectra collected at times when the tide was between its monthly mid-point and its lowest value. We have 170 high-water cases and 163 low-water cases. From Figure 1, we see that, for “Low Water,” the ocean was still never farther than about 75 m from the CIP. For “High Water,” the ocean was typically no farther than 50 m from the CIP.

In Figure 4 and in other, similar plots for lower wind speeds (not shown), we see no obvious differences between the spray concentration spectra collected during high water and during low water. Henceforth, we analyze both sets of measurements together.

RESULTS

Figure 4 demonstrates a surprising similarity in the shapes of the concentration spectra at all wind speeds. We thus nondimensionalized all spectra collected in all wind speeds of 5 m/s and higher with the concentration measured in the radius bin centered at $6.25\ \mu\text{m}$, the smallest CIP size bin, where we have the best counting statistics. Figure 5 shows these nondimensional spectra. As Figure 4 hinted, the spectral shape is surprisingly consistent regardless of the wind speed.

The spectra in Figure 5 suggest straight-line behavior in this log-log plot for both the four bins at small radii and the six bins at large radii. The two straight, black lines in Figure 5 show our fits to these bins.

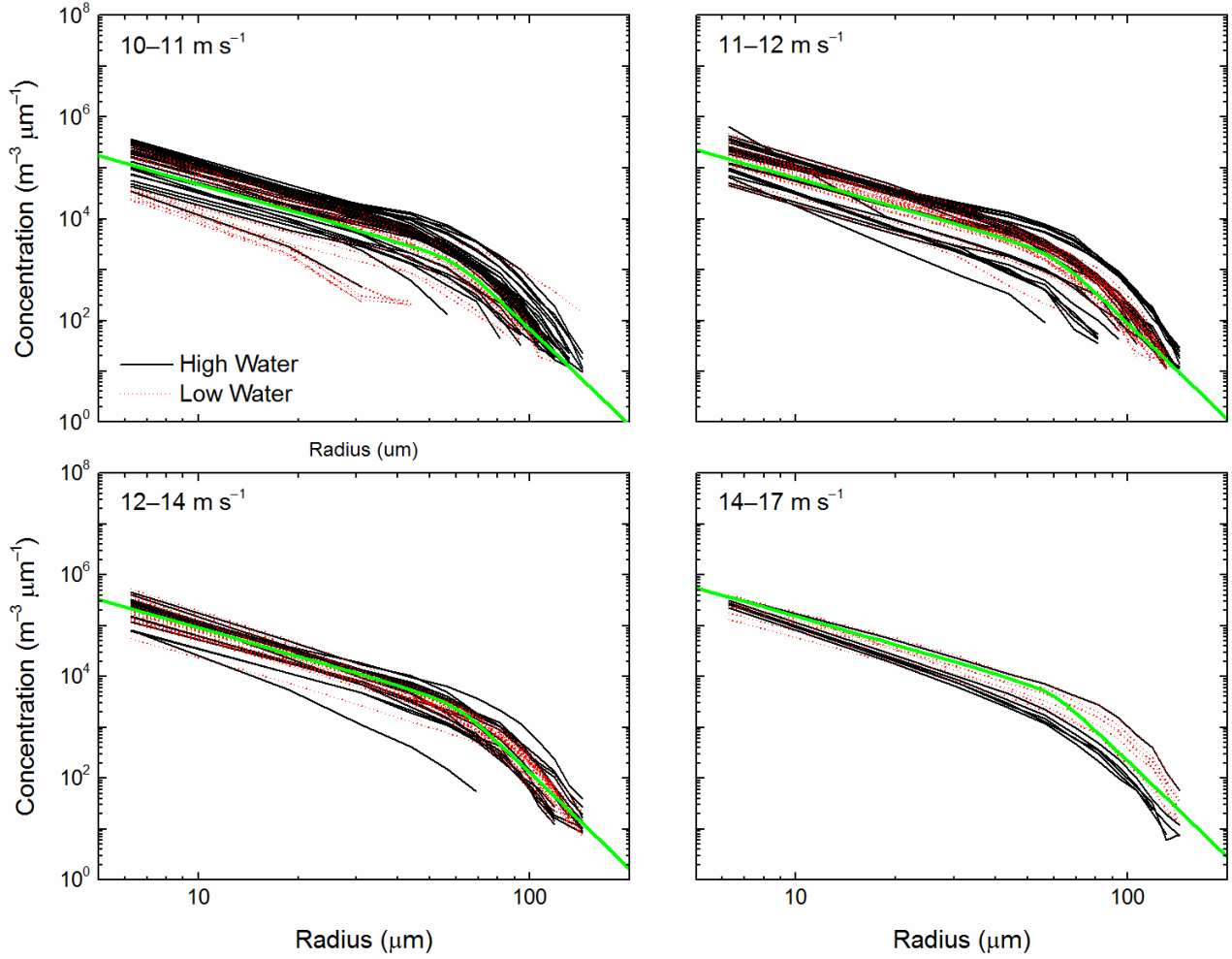


Figure 4. Half-hourly averaged, near-surface spray droplet concentration spectra (i.e., C_0) for wind speeds (U_{10}) between 10 and 17 m/s. The black and red curves distinguish between measurements made during high water and low water, respectively. The green curve in each panel is our fit to these concentration spectra, (3), where U_{10} for each green curve is the middle value of the wind speed range indicated in the upper left corner of each panel.

Because the spectra in Figure 5 asymptote to straight lines for large and small radii, we can represent the entire nondimensional spectrum with a single hyperbola in radius. That hyperbola is

$$\ln[C_0(r_0)/C_0(6.25\mu\text{m})] = -4.20022 - 4.08587 \left\{ [\ln(r_0) - 4.10051] + \left[0.29891[\ln(r_0) - 4.10051]^2 + 0.0078383 \right]^{1/2} \right\}. \quad (1)$$

Here, $C_0(r_0)$ is the spray concentration for radius r_0 extrapolated to the ocean surface; $C_0(6.25\mu\text{m})$ is the concentration in the radius bin at $r_0 = 6.25\mu\text{m}$ that we used for nondimensionalizing; and r_0 must be in micrometers.

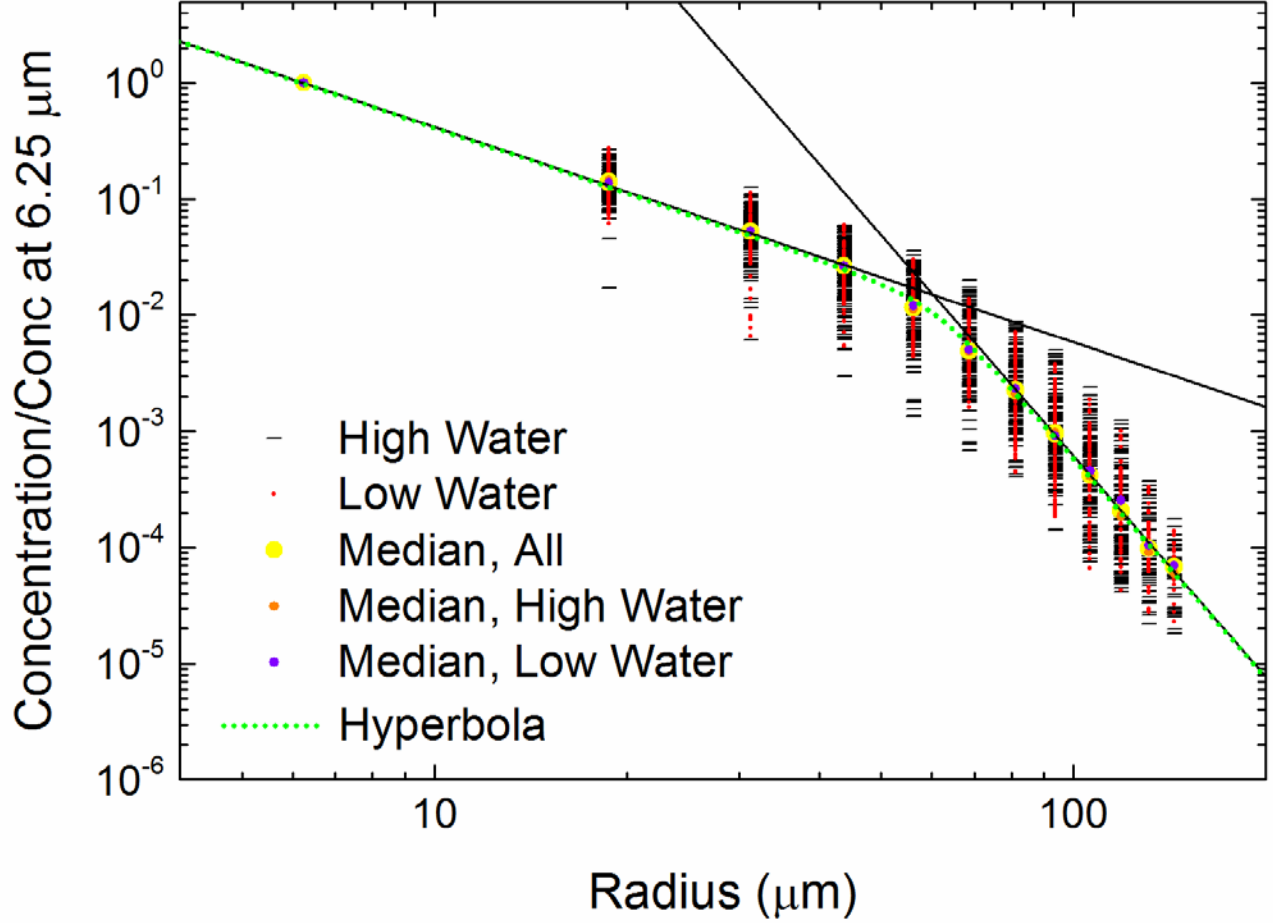


Figure 5. All measured spectra for winds from 5 to 17 m/s (e.g., Figure 4) are nondimensionalized with the respective concentration measured for the radius bin centered at $6.25 \mu\text{m}$. Hence, all spectra are identically one for $r_0 = 6.25 \mu\text{m}$. The plot still distinguishes measurements made during high water from those made during low water; though, again, we see no differences. The plot also shows the bin medians for all the data and for just the high-water and low-water data. The bins for small radii and for large radii fall along straight lines on this log-log plot (the two black lines). We thus represent the median nondimensional spectrum with a hyperbola, (1).

To actually implement (1), we need to know how $C_0(6.25 \mu\text{m})$ depends on the wind speed at 10 meters, U_{10} . Figure 6 shows our 333 measurements of the droplet concentrations in the smallest radius bin, $6.25 \mu\text{m}$ [i.e., $C_0(6.25 \mu\text{m})$] as a function of U_{10} . The line fitted through these data is

$$C_0(6.25 \mu\text{m}) = 100.38 U_{10}^3. \quad (2)$$

Here, C_0 is in number of droplets per cubic meter of air per micrometer increment in droplet radius, $\text{m}^{-3} \mu\text{m}^{-1}$; and U_{10} is the wind speed at 10 m in m/s.

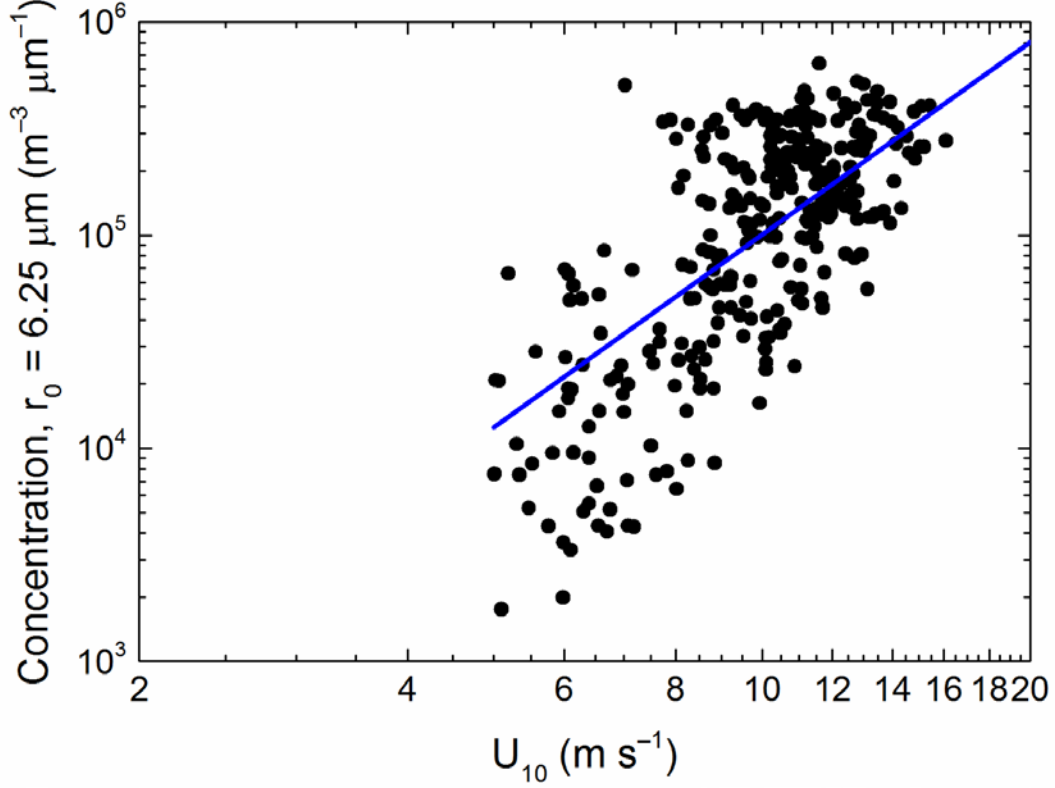


Figure 6. The near-surface cloud imaging probe spray concentration data for the bin centered at $r_0 = 6.25 \mu\text{m}$ [i.e., $C_0(6.25 \mu\text{m})$] are plotted against the wind speed at 10 m, U_{10} . The blue line is the cubic relation (2).

Putting (1) and (2) together yields one of our main results, an expression for the near-surface spray concentration of droplets with radii between 6.25 and 143.75 μm and for wind speeds between 5 and 17 m/s:

$$C_0(r_0, U_{10}) = 100.38 U_{10}^3 \left[-4.20022 - 4.08587 \left\{ \left[\ln(r_0) - 4.10051 \right] + \left[0.29891 \left[\ln(r_0) - 4.10051 \right]^2 + 0.0078383 \right]^{1/2} \right\} \right]. \quad (3)$$

Here, C_0 is in $\text{m}^{-3} \mu\text{m}^{-1}$ when U_{10} is in m/s and r_0 is in μm .

DELIVERABLES

This is a basic research project: We are not building things. Rather, our products are basic knowledge that is generally disseminated in the scientific literature or at scientific conferences. As such, in the last two years, we have published two papers and made four conference presentations and have also published associated proceedings papers. The journal papers are Andreas et al. (2015) and Vickers et al. (2015); the proceedings papers are Andreas (2014), Andreas et al. (2014), and Jones and Andreas (2013a, 2013b).

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